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DEVELOPMENT OF A DESIGN METHODOLOGY FOR SLIPBAND OBTURATORS

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Modern 105-mm kinetic energy (KE) fin-stabilized ammunitions are designed to spin at much lower rates than are created by the rifling in a M68 tank gun barrel. Spin reduction is achieved using slipband obturators. The development of a slipband obturator design methodology through a Department of Energy (DOE)/Department of Defense (DOD) Memorandum of Understanding (MOU) is discussed. The results of tests to compare the existing, a previous, and alternative band designs are discussed along with suggestions for future designs.

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1. INTRODUCTION

Rifled gun tubes impart spin to the projectiles fired through them. Traditionally, projectiles were of such dimensions that high spin rates stabilized their flight. This allowed the progression from ball-shaped projectiles to longer, sleeker projectile shapes which increase achievable range and accuracy. The advent of long-rod projectiles brought the necessity for a different type of stabilization. These projectiles are fin stabilized and while they still spin, they must be spun at much lower rates than the spin-stabilized projectiles. In order to fire both classes of projectile from the same gun, some mechanism was required to provide the correct spin to the respective projectile.

An understanding of the mechanism for imparting spin to a projectile leads toward a method of altering spin of the projectile. A spin-stabilized projectile has a rotating band of either metal (usually lead, copper, or brass) or plastic which is securely attached to the projectile. The lands of the rifling in the gun tube engrave into the rotating band and force the projectile to follow the path of the rifling as it traverses the length of the barrel. Obturation, or sealing, is achieved by the interference fit of the soft band with the inner surfaces of the gun tube. Sometimes additional sealing is required and an obturator is added to the projectile. This may be a rubber seal added to the base of the projectile. A method used to reduce the spin of a projectile is the slipband obturator. The paradox of this design is that the element which engages the rifling must both seal the combustion gases from escaping by or through the projectile while being disconnected enough not to impart its full rotation to the projectile body. Nevertheless, such a band was developed and successfully implemented on the M735 fin-stabilized discarding sabot kinetic energy (KE) projectile. This slipband, developed at Picatinny Arsenal, NJ, in the late 1960s and early 1970s, consists of an inner sealing band made of polypropylene and an outer obturator made of nylon 6/6.

2. DEVELOPMENT OF THE DESIGN METHODOLOGY

In recent years, the development of long-rod KE projectiles created a resurgence of interest into the mechanism and design of slipband obturators. The U.S. Army Ballistic Research Laboratory (BRL) felt the importance of understanding the mechanism great enough to warrant a moderate study effort into the phenomenology. Through prior interactions with

the Department of Energy's (DOE) Sandia National Laboratory in Livermore, CA (SNLL), BRL knew of their interest and ongoing work in the area of obturation and torsional impulse. A Department of Army (DA)/DOE Memorandum of Understanding (MOU) was established to study the issue of slipband technology.

SNLL had been performing significant work both in dynamic response finite element modelling of copper obturator bands and on experimental studies of the strain and extrusion process of copper bands as they made the transition through the gun's forcing cone and the constant diameter of a smoothbore gun tube (Nielan, Perano, and Mason 1990; Perano 1988). Large efforts were made to increase their computational abilities to study a nylon obturator band. This required continuation on code work which included two-dimensional (2D) rezoning capabilities to refine and redefine the finite element mesh due to the large deformations encountered by the extruded band materials. It also required the establishment of material properties for the plastics which were used in the slipband obturator. Dan Dawson of SNLL studied the properties of many plastics and combinations of plastics which may be considered for use in this application (Perano 1988). He found that the polypropylene and nylon combination already in use was one of the best of those he studied. In addition, he studied the use of several different lubricants applied to the plastics and their effect on the static and dynamic friction at their interface. The slipband obturator design in current production includes the use of a silicon lubricant.

Many characteristics of polymer properties were studied by Kawahara, Brandon, and Korellis (1983) at SNLL. They have modelled and experimentally studied the effects on materials' mechanical behavior of temperature, moisture, and rates of loading.

Paul Nielan of SNLL worked on the development of a computer code called BANDSLIP which is used to predict the exit spin velocity of a projectile given the base pressure input to the projectile, the initial geometric conditions of the obturator within the gun tube, and the mechanical and thermal properties of the band materials (Nielan and Benedetti, to be published). This predictive code is based on the following theory.

The band's interference with the projectile body and gun tube wall, due to its geometry, creates an initial condition called band pressure. The material selection and temperature define a coefficient of friction within the band assembly. The combination of the forces acting on the interface of the inner and outer bands and the coefficient of friction of the interface control the amount of torque which may be transmitted to the projectile body from the gun barrel's rifling. The code assumes the inner band does not rotate on the projectile body and the outer band must follow the path of the rifling. There are two surfaces within the band configuration where torque may be transmitted. The radial surface's ability to transmit torque is largely controlled by the band pressure which compresses the surfaces together. The base pressure controls the force on the front surface interface. A diagram of these surfaces is shown in Figure 1.

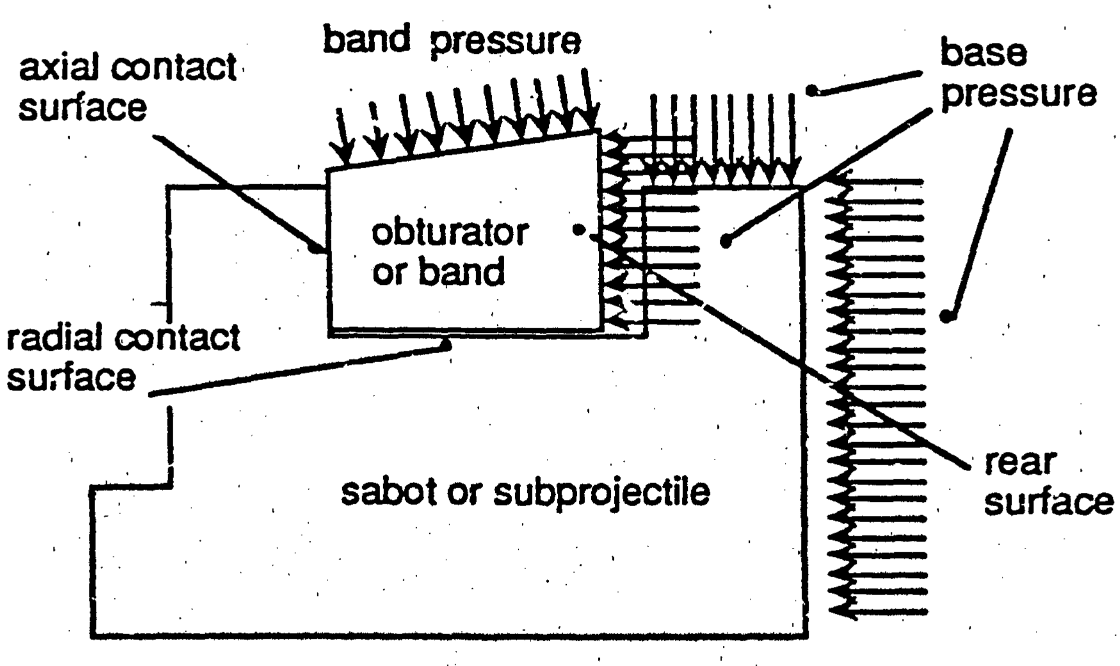

Figure 1. BANDSLIP Modelling Considerations.

The code predicts the progression for torque transmission of the nylon/polypropylene slipband. Initially, band pressure and the friction coefficient are great enough to transmit sufficient torque for the projectile to rotate at the rate of rifling. Evolving gas causes increased base pressure which accelerates the projectile linearly and, therefore, also rotationally. The outer obturator band is assumed to seal against the gun wall. Gas infiltrates between the radial surfaces of the inner sealing band and the outer band, with the assumption that no gas escapes past the front surface of the obturator band. Therefore, as base pressure increases, the normal force on the front interface increases and the normal force on the radial surfaces decreases from its initial value, which was the result of the input band pressure. As the projectile is forced down the gun bore, the rifling forces the outer band to rotate at the twist rate of the rifling. For a while, full torque is transmitted between the bands, but eventually, as the base pressure increases, the radial surfaces are separated and no torque is transmitted there.

If the surfaces cannot transmit the full torque imparted by the rifling to the accelerating projectile, slippage begins. The heat generated by the slippage of contact surfaces increases the temperature of the interface until the polypropylene melts. Polypropylene has a much lower melting temperature than nylon. If the surfaces are not in contact or one of the surfaces has melted, the ability of that interface to transmit torque is assumed to cease. At the time when torque can no longer be transmitted, the projectile continues to accelerate linearly down the gun tube but has reached its terminal rotational velocity.

This theory matches up generally well with evidence from actual gun firings. Slipband obturator components found after sabot discard reveal that the inner surface of the outer band often is in an as-machined condition (McCall and Burns 1988). All that typically remains of the front surface of the inner band is a small nub. The outer, or obturator, band is often forwardly and rearwardly extruded. This correlates with SNLL's other findings on obturators both analytically and experimentally. The predicted trend that rounds fired at 120° F should reach lower spin rates than those fired at 70° F, which should be lower than those fired at -20° F, has not been seen to hold true. Experiments have resulted in projectiles which have had higher and lower spin rates at both elevated and decreased temperatures as compared to spin at "standard" temperatures. The code's predictions are based on the time necessary for the heat generation to raise the materials from their initial temperature to their melt

temperatures. It does not account for different band-pressure values due to the thermal expansion of the materials in the band, gun, or the projectile. The geometric differences in the size of the components could be inputted, but this does not automatically affect the value of the band pressure.

In fact, two unknown inputs into the prediction are band pressure and the coefficient of friction. Reasonable values have been established as inputs, but they are based on empirical understanding of the system. The code has the ability to generate families of values of both band pressure and coefficient of friction, which will result in predicted values of exit spin rate. An example of this is shown in Figure 2. Knowledge of any two of these parameters will allow determination of the third.

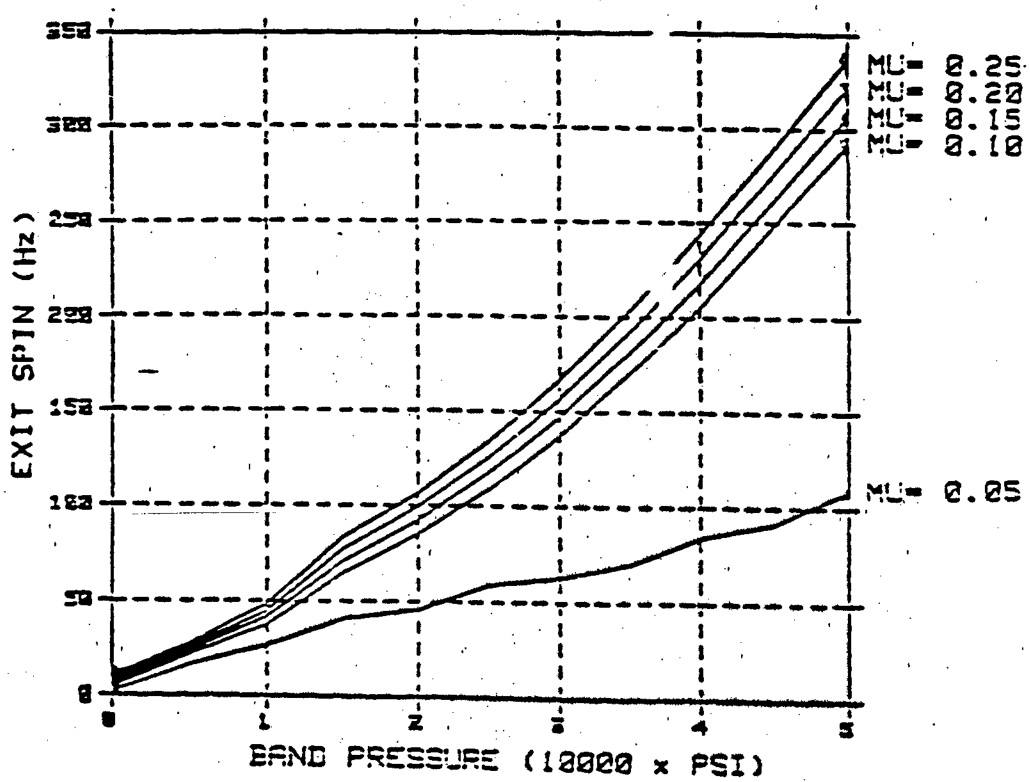

Figure 2. Family of Exit Spins for Slug Projectiles Predicted by BANDSLIP.

The theory is, however, quite believable and helpful in making design considerations for slipband obturators. The selection of materials can be used to alter the coefficient of friction, which controls the initial condition of spin up, and the melting temperature, which will control the final spin rate if slippage occurs. Geometric considerations in the design affect the initial band pressure and the interval of time for the base pressure to reduce the band pressure's component in torque transmission. The geometry also controls the rate at which the loading on the front surface will generate heat and cause melt to occur.

BRL has and is performing a series of gun firing tests which are designed to study the slipband obturator (Burton, Kaste, and Stobie 1989). A useful tool developed is a 37-mm rifled gun tube, which was machined down to a 1/4-in. wall thickness over the region of projectile travel and then overwrapped with graphite/epoxy to provide structural support. This allows the projectile to be observed through the bore using 450-keV flash x-rays, which are available in one of BRL's indoor ranges. This technique was used to determine the in-bore rotation of the projectile as it traverses the tube. Copper rotating bands were shown to rotate at the rate of the rifling, and a slipband design based on the band used on M735 projectile was shown to limit the rate of rotation of the projectile body to about 10% of that of the rifling as seen in Figure 3. The phenomenon of onset of a greatly reduced rate of projectile rotation relative to the rate of rifling at a short distance of projectile travel predicted by the code was observed in these experiments.

3. DESIGN VERIFICATION THROUGH EXPERIMENTS

The U.S. Army Armament Research, Development, and Engineering Center (ARDEC) designed a series of tests using 105-mm slugs, which was performed by the U.S. Army Combat Systems Test Activity (CSTA) at Aberdeen Proving Ground, MD, to study various slipband configurations. Unfortunately, sparse resources limited the extent and perhaps usefulness of this testing. The various designs considered are shown in Figure 4. The rationale behind the various designs and modifications are as follows.

A. "M833" band - "J band" also used on the M735 projectile used as a baseline indicator.

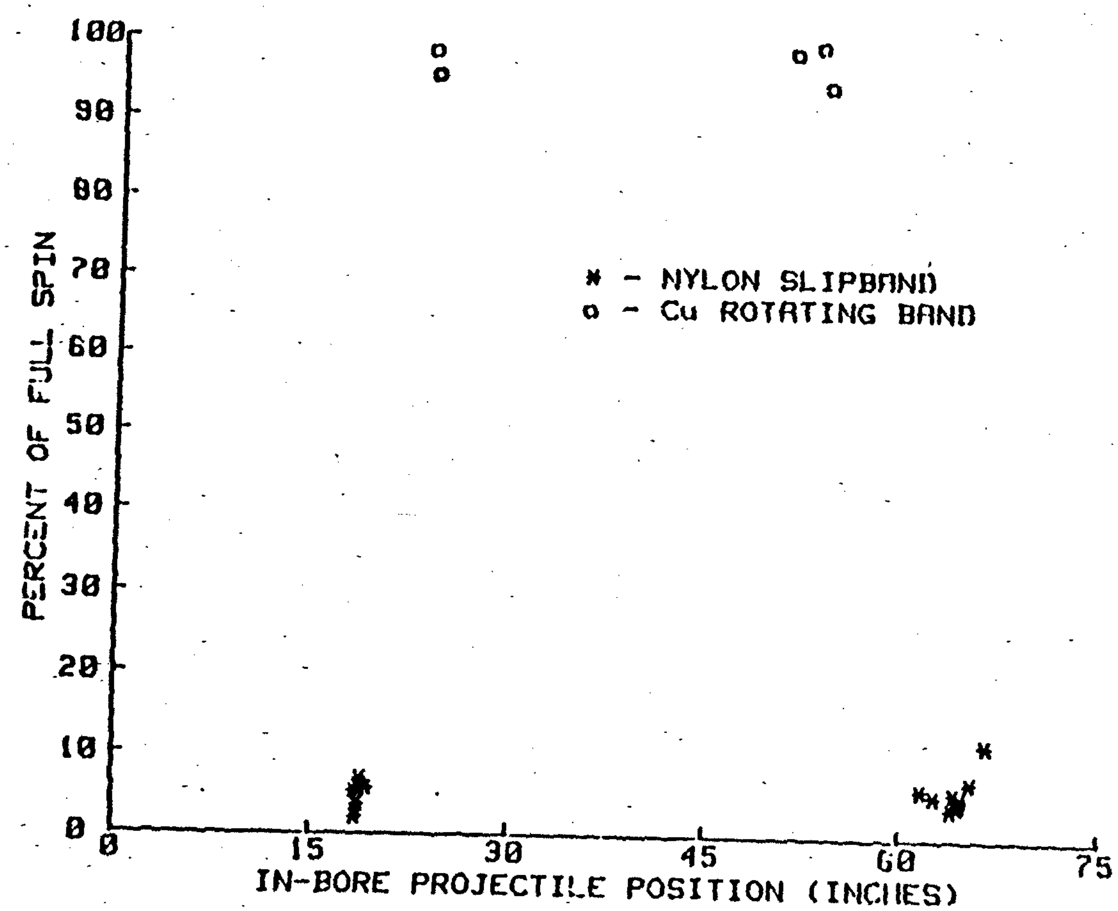

Figure 3. Experimental Results of Through-Bore Radiography Study of Slugs With Copper Rotating Bands and Slipband Obturators.

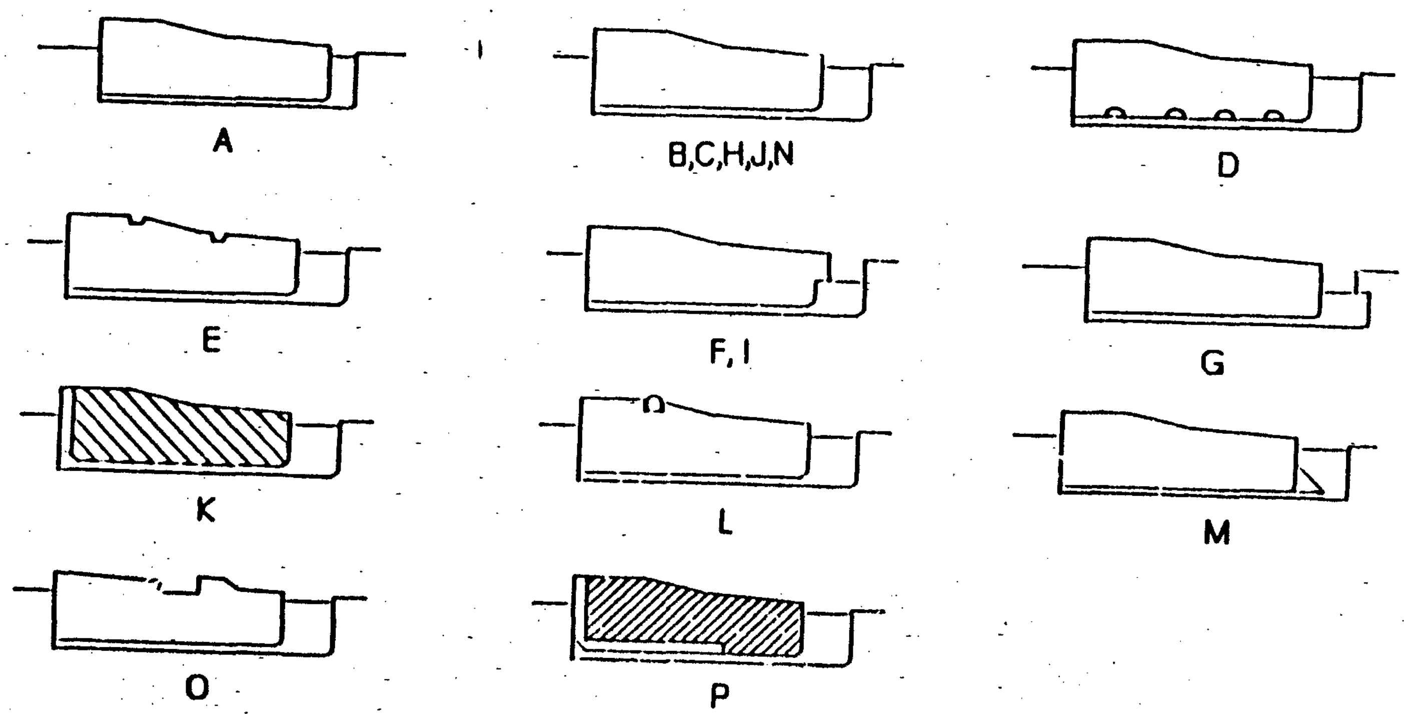

Figure 4. Band Configurations Tested on Slug Projectiles.

B. "STANDARD" band - Band currently in use. It has twice as much material on the front lip of the inner band than the "M833." This is to ensure that polypropylene is not consumed before muzzle exit. This has not been verified. This band was used as a baseline indicator.

C. "PETROLEUM GREASE" band - "STANDARD" band but substituted petroleum grease for the silicon lubricant currently used. Laboratory investigations showed this grease may reduce the static friction coefficient of this system. Its use was to see if this lowered coefficient of friction would lower the threshold of slippage during the early phase of motion before base pressure creates a clearance between the band components.

D. "CIRCUMFERENTIAL GROOVES" band - "STANDARD" band with circumferential grooves cut into the underside of the obturator band to promote the "air bearing effect" of the gases between the band components.

E. "CANNELURE GROOVES" band - "STANDARD" band with cannelure grooves cut into outer surface of the obturator band to reduce band pressure by changing the initial contact positions of the band with the gun tube wall and by creating stress relief for compressed obturator.

F. "OVERHANGING OBTURATOR" band - Forward surface of the inner band is standard thickness, but reduced in height. Obturator is cut back in front to overhang the inner band. This is to entrap the molten layer of polypropylene as it is formed, creating a more effective bearing and extending the life of the molten polypropylene bearing.

G. "OVERHANGING SABOT" band - Creates an entrapment system for the molten layer as in the previous band but maintains the original amount of material of the "STANDARD" obturator band, although not as effective in preserving the molten layer as it is first generated.

H. "TIGHT STANDARD" band - Same band as "STANDARD" but processing of the installment is adjusted to create a tighter fit after installment.

I. "OVERHANGING OBTURATOR WITH PETROLEUM GREASE" band - Investigated to determine effect of the different lubricant on the "OVERHANGING OBTURATOR" which showed to be effective.

J. "LARGER ID" band - Material was removed from the inner diameter of the "STANDARD" obturator to reduce band pressure by reducing the interference of the band between the gun tube wall and projectile body.

K. "SANDIA" band - Based on a design by SNLL which was intended to more freely allow gases to infiltrate between the band components while maintaining the proper location of the obturator. Sixteen grooves were to be cut into the obturator surfaces. Radial grooves in the rear surface were .05–.06 in. deep with a radius of about .03 in. Longitudinal grooves in the inner surface were .04–.05 in. deep with a radius of about .03 in. However, the original design broke during installation. The longitudinal slots on the inside radial surface of the obturator were eliminated and the resulting band was used. The operational intent of the design is to quickly reduce band pressure and initiate slippage.

L. "O-RING" band - Not originally designed to reduce spin, this band was included as a form of the "CANNELURE GROOVE" concept with added obturation during initial pressurization provided by the O-ring.

M. "NOTCHED SEALING BAND" band - Uses the shown effectiveness of the reduced front surface contact in the overhanging concepts. This design was conceived to exploit the reduced area and increase the slipping velocity by increasing the radius of the contact area. The design should also provide entrapment of the molten layer.

N. "REDUCED OD" band - The reduced outer diameter of the obturator was intended to reduce the interference with the gun wall and projectile.

O. "520T" cannelure groove band - A band design from Chamberlain Corp. which had shown to be effective in prior testing was evaluated. Reduced band pressure by allowing space for material flow, but improved obturation design over the "CANNELURE GROOVES" warranted its inclusion.

P. "SANDIA MOD" band - A band based more closely to SNLLs original concept was tested. Twelve longitudinal and radial grooves were used with radii of .100 in. cut .015–.020 in. deep into both surfaces.

Designs A through G were tested in the first test series. Designs B, F, and H through M were tested in the second series. Designs A, B, and N through P were tested in part three of the testing. Lack of resources precluded the reevaluation of design G which required modification to sabct. Sample sizes were groups of five in the first two test series and groups of three in the third of the series.

4. RESULTS OF EXPERIMENTS

Using one-way analysis of variance reveals the following from this data. The velocity means for slugs with band design A fired in tests 1 and 3 are different. However, the velocities determined for band design B are considered to be equivalent in all three tests. Likewise, the velocities determined for band F are equivalent in tests 1 and 2. Designs with velocities less than the standard band (B) are E, J, K, M, N, 0, and P.

The chamber pressure means for band design A were also determined to be different between tests 1 and 3. The difference correlates with the difference found in velocity. Once again, means for band designs B and F were determined to be equivalent in their respective tests. Chamber pressures that can be considered less than standard (B) are J, K, and O.

Band designs A, B, and F all were found to have equivalent spin values between their respective test groups. Spins that were found to be higher than the standard band (B) were designs A and N.

5. DISCUSSION OF RESULTS

Using the one-way analysis of variance, it is difficult to determine the differences in variability between band designs. All values determined for band designs B and F were found to be equivalent statistically. Likewise, spin values for design A were found to be equivalent between tests 1 and 3. However, the scatter in data produces large standard deviations when

combining data from the different tests. Pooling the data between tests results in apparent improvement in variability for all designs as compared with design B, which was evaluated in all three tests. Clearly, this is an artifact of the small populations and the occasion to occasion variability of the data available. Unfortunately, this forces more subjective evaluations from the available data. Pressure and velocity results are indications of a band design's obturation performance. They may, however, be indicators of resistance to engagement with the rifling and compression through the forcing cone of the gun. Data collected in the tests include high-speed photography of a view looking into the bore of the gun. These records provide information on the obturation on the projectile. Many of the band designs which yielded lower pressures and velocities were not shown to have provided poor obturation as evidenced by photography of little or no flashes of light while the projectiles were in-bore. The projectiles could not be recovered, so physical data on obturator leakage and wear were lost. The photographic evidence infers the conclusion that the in-bore resistance to travel was reduced. In future testing, propellant charges for projectiles using these bands should be adjusted to determine spin rates at equivalent velocity and chamber pressure.

The one-way analysis of variance test reveals that only designs A and N result in an increase in spin as compared to design B. The spin produced by design A could be expected to be greater than standard (B) from the theory explained previously. The increase in spin due to design N is not so easily explained. On the surface, one might expect design N to behave like design J. Both result in a thinner obturator band which should reduce band pressure and ease the infiltration of combustion gases; however, the overall results are different. Velocities are lower for both than standard, but only band J has lower chamber pressure (and, thereby, presumedly lower base pressure). Design J has equivalent spin as standard, but design N has greater spin. However, it might be noted that design J does have greater spin than design B in the test in which both were actually fired and the spin for N is borderline equivalent to design B in the overall comparison. The pressure for design N is marginally equivalent to that of design B, shading towards being lower than B.

To conclude that designs J and N may be, in fact, equivalent in having provided reduced velocities and pressures with greater spin than the standard band requires a rational explanation to avoid conflict with the assumed operating theory. One explanation which can be made is that the reduced chamber pressure and projectile velocity were caused by

combustion gases flowing over the obturator. Reduced base pressure and pressurization from above would allow the band pressure to remain high, transmitting more torque to the projectile and increasing spin rate. If reduced chamber pressure and velocity were caused by reduction of in-bore resistance to travel and obturation was maintained, the spin rate would be expected to be equivalent or lower than that of a standard banded projectile. It could be possible that obturation is occurring in an unconventional fashion. Gas leakage over the top of the obturator during the initiation of pressurization could force the obturator down, creating a seal with the inner or sealing band. Later, when the obturator has travelled completely through the forcing cone, it could obturate properly against the gun wall. Exclusion of combustion gas from between the bands would prevent the decrease in the normal force in the radial contact region, thereby, increasing the spin rate.

Figures 5 through 7 present the data from the three tests. The error bands for each design are plotted between the mean ±1/2 (standard deviation). The complete data sets from each of the three tests are shown. The one-way analysis of variance includes these data and uses a pooled standard deviation and the number in the sample population to reflect upon the independence between data sets. Using this analysis, the spin behavior of design B is considered equivalent in all three tests.

Several results of modifying the standard obturator can be seen at least qualitatively. It appears as though the strength of the obturator or the support provided to the obturator is at a critical value. In all cases where material has been removed and left a region unsupported (designs D, E, K, M, and P), a reduction in velocity occurred. Design F, which has material removed but provides support to this region, does not show this reduction. Design L, where material is removed but is somewhat supported by the addition of the O-ring, shows some reduction in velocity but not to the same degree as the other designs. Even designs K and P where one would not expect a significant reduction of support in the obturator, show reduced velocity. While design O also shows reduced velocity (and it has unsupported regions), its design is not as closely based on the standard design as the others.

Additionally, one can make an observation from design C, "petroleum grease." Pin on disk experiments at SNLL (Perano 1988) predicted that this grease should decrease the coefficient of friction and reduce spin rate. What was observed was a large scatter of spin rates which

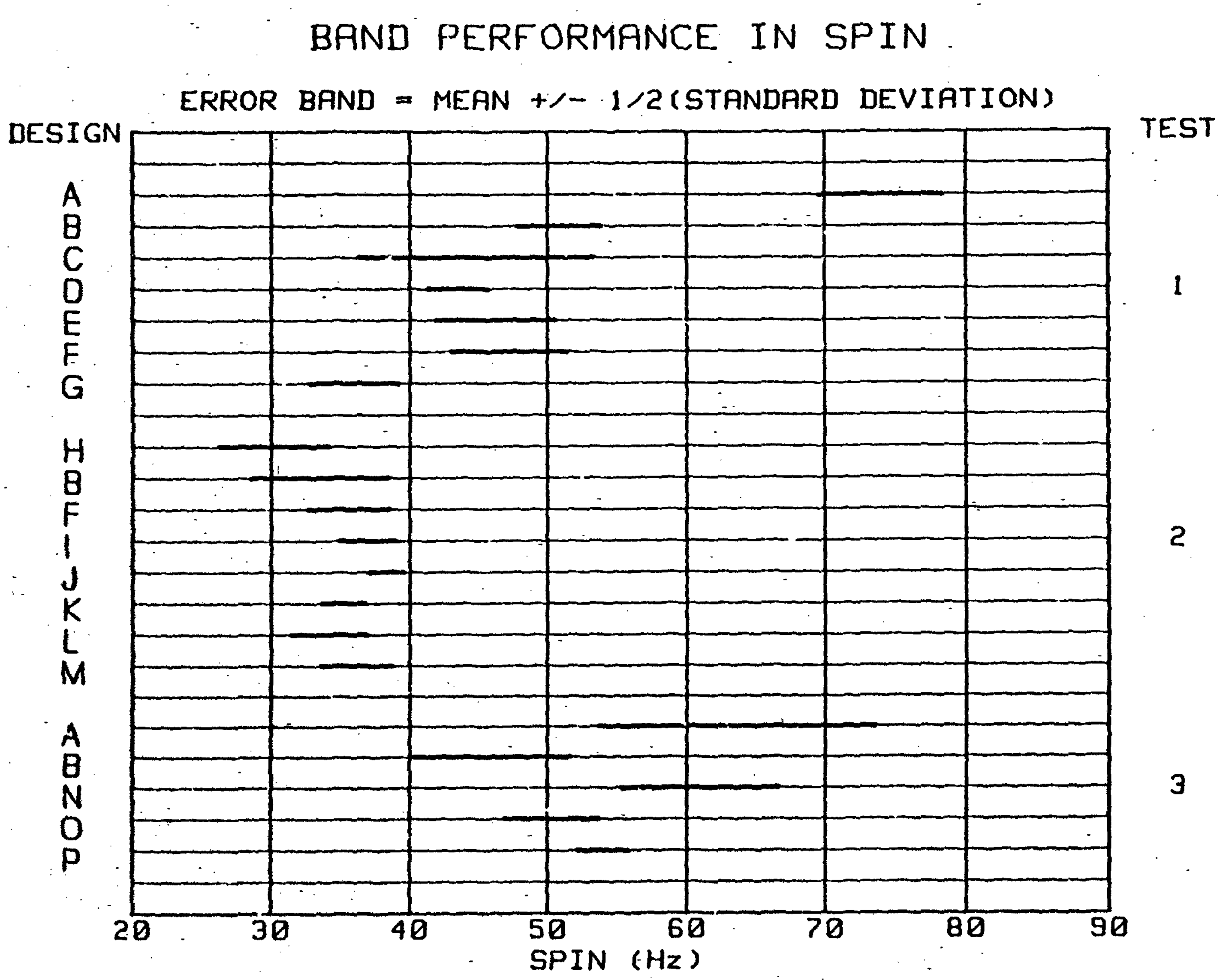

Figure 5. <u>The Effect of Band Design on Spin</u>.

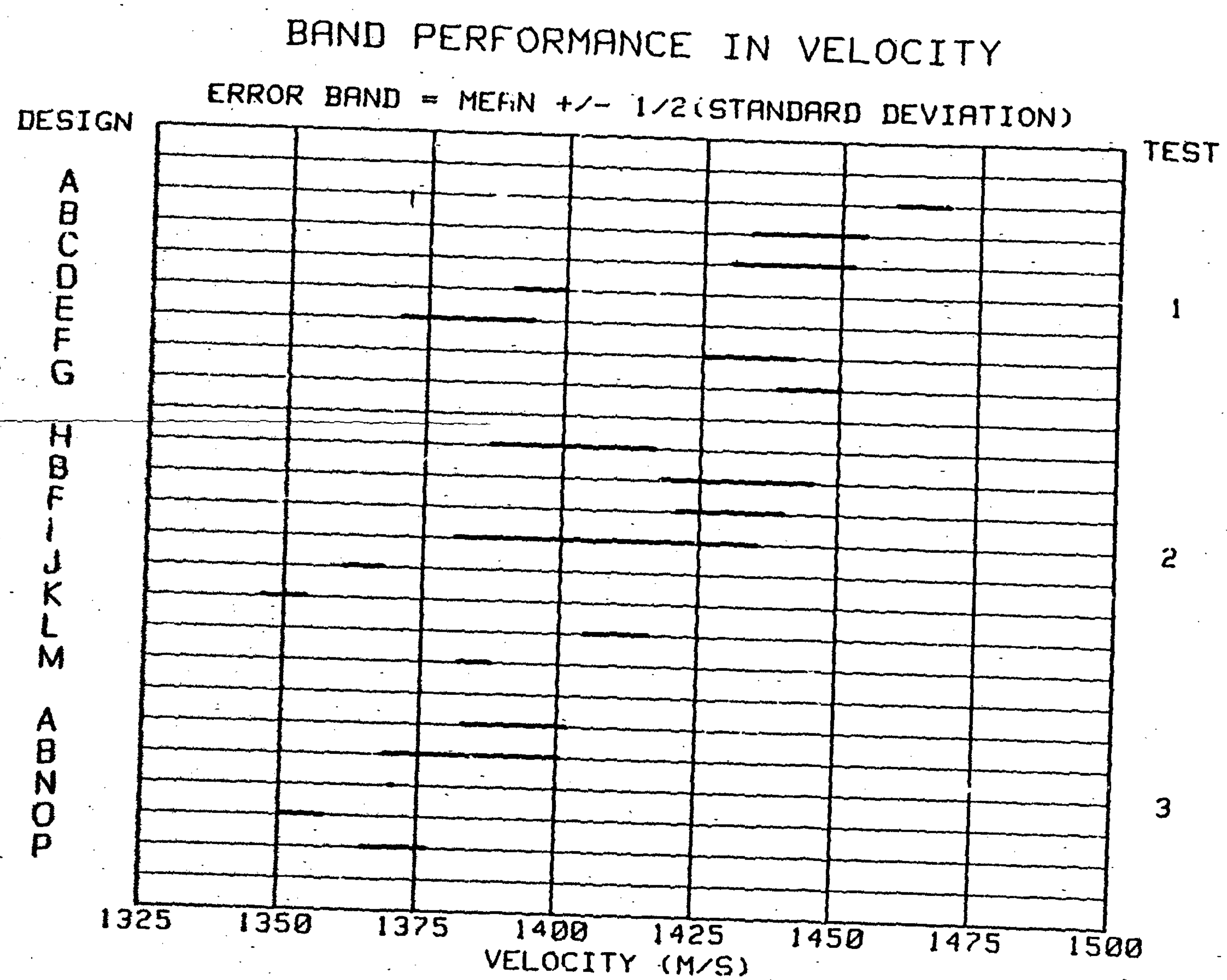

Figure 6. The Effect of Band Design on Velocity.

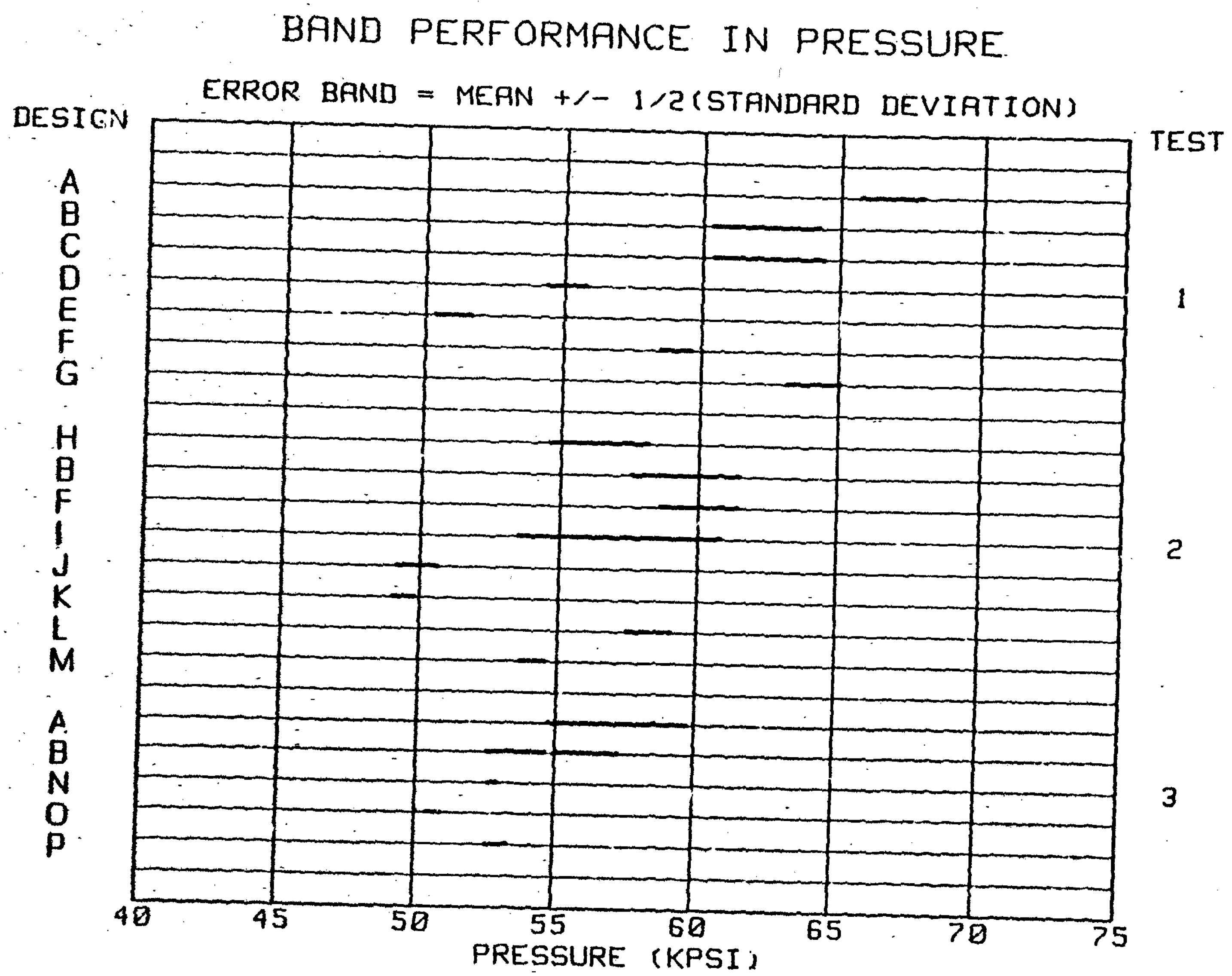

Figure 7. The Effect of Band Design on Chamber Pressure.

included some cases of reduction. In this application, one with small clearances and a highly loaded bearing interface which operates only for a very short duration, lubrication by the application of a hydrodynamic film might be suspect. Substances such as greases and oils generally require some run-in time to create the hydrodynamic films through which they provide lubrication and reduce friction. These conditions of operation, where the inner band rotates less than two revolutions relative to the outer band over a time period of less than 10 ms, are not conducive to this. The variation in the ability for this film to form may be evident in the variation in spin rate observed for this design.

Variation in performance, including spin rate, is often considered an important feature of a slipband's design. Naturally, small variation in performance is desirable, but not always easily achievable.

The results from the designs tested all provide agreement to the basic theory of spin generation of BANDSLIP. Reducing the torque-carrying ability of the band system through alteration of the coefficient of friction or reduction of band pressure reduces the rate of spin of the projectile as it exits the gun. Analysis of the data from these tests has led to a better understanding of the operation of the slipband obturator and towards another generation of design.

Features which are important to a slipband obturator system are as follows:

I. Low static and dynamic coefficients of friction at the slipping surfaces. This is a factor of the materials chosen, surface and geometric effects at the interface, and lubricant, if employed.

II. If a lubricant is used, it must be able to reduce friction from a static situation without much time or motion for the generation of a hydrodynamic film.

III. The ability to limit torque transmissivity via reduction of the normal force between slipping surfaces or reduction in coefficient of friction (shear-load transmission). This class of design provides these features through gas infiltration between the band components and through one component of the slipping interface becoming molten.

IV. If a material is to be sacrificial, there must be enough material or a mechanism to ensure this material survives throughout the entire travel through the gun tube.

V. The obturator must have sufficient strength and be of proper design to provide good obturation against the gun wall throughout the ballistic cycle without increasing the normal force between projectile and the obturator or preventing other mechanisms from reducing the normal force.

VI. The area of the bearing surface is important as a control of time to melt and volume of material available for consumption given a fixed length of obturator. It also influences the band's ability to obturate.

6. CONCLUSION

The current version of BANDSLIP is not refined enough to predict the effect of small details in an obturator design on the projectile's spin rate. In order to use purely analytical methods to create obturator designs which provide optimum ballistic performance including spin, more complex models are necessary. The model would have to be able to calculate band pressure as a function of geometrical interference and loading due to changing geometry as the obturator passes through the forcing cone and base pressure rise, rather than the empirical input currently used. It would have to determine which interfaces act as seals and which do not as a function of time and travel. In a more complete model, band pressure would be treated as a gradient rather than the average value as currently implemented. A more complete modelling of temperature effects would also be needed to account for thermal expansion. These factors might simply be accounted for and incorporated into the geometry and material property inputs to the code. The effect of loading rate and humidity on the material properties would also need to be incorporated. The ability to calculate the consumption of the molten material and formation of a new friction surface would make for a more complete model. Inclusion of all these factors could provide not only an extremely useful technique for analytical obturator design but also a method to find causes for round to round variability within a design. Development of such a tool is not an impossible task, but one that has yet to be achieved.

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